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VALIDATING A MODEL OF TEAM COLLABORATION¹

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A model of team collaboration was developed that emphasizes cognitive aspects of the collaboration process and includes the major processes that underlie this type of communication: (1) individual knowledge building, (2) knowledge interoperability, (3) team shared understanding, and (4) developing team consensus. This paper describes research conducted to validate this model and determine how these processes contribute to team performance by analyzing two collaborative decisionmaking tasks. Team communications that transpired during two complex problem solving situations were analyzed and coded. Data was analyzed for two teams that conducted a Maritime Interdiction Operation (MIO) and four teams that engaged in an air-warfare scenario. The MIO scenario involves a boarding team that boards a suspect ship to search for contraband cargo (e.g. explosives, machinery) and possible terrorist suspects. The air-warfare scenario involves identifying air contacts in the combat information center of an Aegis ship.

INTRODUCTION

Military forces are beginning to operate as a networked force, which allows them to plan, decide, and act collaboratively and concurrently to accomplish many tasks simultaneously. These collaborative capabilities are expected to contribute to reducing the time required to accomplish military objectives. Rapid access to current, accurate, and relevant information, and the ability to engage in real-time collaboration with other decisionmakers who are geographically distributed, have become indispensable elements of the command and control (C2) planning and decision-making process. While information access has always been critical to success in military operations, the processes embodied in recently emerging military concepts (e.g., rapid decisive operations) place an even greater emphasis on having rapid access to relevant and accurate information. These new military concepts derive their power from the effective linking or networking of the warfighting enterprise (Alberts, Gartska, and Stein, 2003). This new way of conducting business is characterized by the ability of geographically dispersed forces to create a high level of shared awareness that can be exploited to achieve rapid decisive operations.

While the U.S. has an unmatched ability to gather information on the environment, the adversary, and ourselves, we currently lack the collaborative planning capabilities (both mature systems and practiced operators) and C2 systems to use this information to enable decision

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superiority. The ability to quickly create and leverage superior knowledge is a critical aspect of effective military operations. This rapid formulation of knowledge and understanding of the battlespace should enable decision superiority, reduce operational risk, and increase the pace, coherence, and effectiveness of operations.

The need for rapid access to current, relevant, and accurate information is at an all-time premium — especially for military operations. Moreover, the need for expeditious transformation of that information into “actionable” knowledge is increasingly recognized by the warfighter. This exchange and transformation of information to support the military decisionmaker is facilitated by a shared information environment, and the tools that enable collaboration. New Information Technology (IT) Tools, used as part of a networked, web-based collaborative system for command and control are providing enhanced capabilities for improved decisionmaking. These tools support planning and operational processes by providing an alternative means to communicate, collaborate, and share information among operators and decisionmakers than were provided in past operational environments.

Concepts such as information and knowledge superiority, knowledge management, and effects-based operations, are important enablers of effective military operations. The need to accomplish missions efficiently and effectively, with coordinated action, points to the demand for powerful, reliable, and capable IT tools to support the military decisionmaker. These tools are expected to be critical elements of success for the decisionmaker who will be operating in a constrained battlespace, working toward the goals of achieving shared awareness, information/ decision superiority, unity of effort, and the ability to respond rapidly and autonomously.

Collaborative Tasks

Inherent in many problem solving tasks is the need for extensive collaboration and coordination across functional areas and components within the organization to accomplish the mission. Collaboration tool suites are being introduced to facilitate these information-intensive interactions to support operational planning and decisionmaking processes by providing an alternative means to communicate, collaborate, and share information among warfighters that extends what is available in today’s current operational environments. Enabled by high-speed bandwidth connectivity and electronic collaboration tools, it is anticipated that a collaborative information environment will facilitate the exchange of information among members of the Joint Force and those organizations supporting or being supported by the Joint Force. The long-term goal for operating in a collaborative environment is to reduce planning timelines while increasing organizational effectiveness.

The majority of military and business tasks today are performed by teams who collaborate to share information and task perspectives in order to reach a decision. Benefits afforded by collaboration tools that are especially germane to the military include allowing smaller deployed warfighter footprints, and capitalizing on the synergy of the total command and control infrastructure. Collaborative tools offer the added capabilities of providing the ability to share information and resources, and coordinate among individuals across geographic and temporal boundaries. Collaboration is also essential to developing shared situational awareness among heterogeneous, distributed team members.

Collaboration offers great potential to better enable decisionmakers and operators to plan, monitor, execute, and assess activities across the spectrum of activities. Capabilities afforded by collaboration tools include the ability to share applications, have a virtual workspace, use voice/audio/video, etc. Many, if not all, of the benefits of participating in a face-to-face meeting can be gained using collaborative tools: Information flows quickly, outstanding issues are raised, and a certain amount of brainstorming can occur to arrive at a decision. Additionally, all relevant users, or providers of information, reach a fuller understanding of the issues because they have seen other viewpoints and received a freer flow of information (Truver, 2001).

From a military perspective, advantages of using a collaborative environment include: fewer personnel have to be located in the area of conflict; there are enhanced opportunities to share information among planners and decisionmakers; experts in remote locations can participate in all phases of the planning, decisionmaking, and assessment process; it will increase access to many additional sources of information that previously were not possible; it should reduce the time required for the planning, decisionmaking, and assessment process.

Team collaboration and decision-making in complex, data-rich situations is being investigated to better understand the cognitive processes employed when teams collaborate to solve problems. This paper reports on research conducted under sponsorship of the Office of Naval Research (ONR) Collaboration and Knowledge Interoperability (CKI) program. The research reported in this paper applies definitions of the cognitive processes included in the model to two different decisionmaking domains. Both involve team collaboration to solve complex problems. The Maritime Interdiction Operation (MIO) task involves a Coast Guard Operation to search a suspect ship for contraband material and suspect persons. The second scenario involves a US Navy Aegis cruiser combat information center team identifying air tracks in a Persian Gulf scenario.

Model of Team Collaboration

A cognitive model of team collaboration emphasizing the human decisionmaking processes used during team collaboration was developed by Warner, Letsky, & Cohen (2004). This model applies to collaborative problem solving and includes the major processes that underlie collaborative team problem solving, as depicted in Figure 1. These processes include (1) individual knowledge building, (2) developing knowledge inter-operability, (3) team shared understanding, and (4) developing team consensus. In this paper we describe research conducted to validate the model and determine how these processes contribute to team performance by analyzing two complex decisionmaking tasks.

Many definitions of collaboration are found in the research literature, depending on the researchers discipline and perspective. At the most fundamental level, collaboration refers to the joint effort of two or more agents to achieve a common goal (Nosek, 2003), where collaboration members construct judgments and then act on these judgments. A different definition of collaboration is “the mental aspects of joint problem solving for the purpose of achieving a shared understanding, making a decision, or creating a product.” Yet another definition states that “collaboration occurs when a group of autonomous stakeholders of a problem domain engage in an interactive process, using shared rules, norms, and structures, to act or decide on issues related to that domain” (Wood and Gray, 1991).

The types of problem-solving situations this model describes are ill-structured decisionmaking tasks, characterized by time pressure, dynamic information, with high information uncertainty, high cognitive workload (i.e., a large amount of knowledge is brought to bear), and human-system interface complexity. The model focuses on three tasks; (1) team data processing, (2) developing a shared understanding among team members, and (3) team decisionmaking and course of action selection.

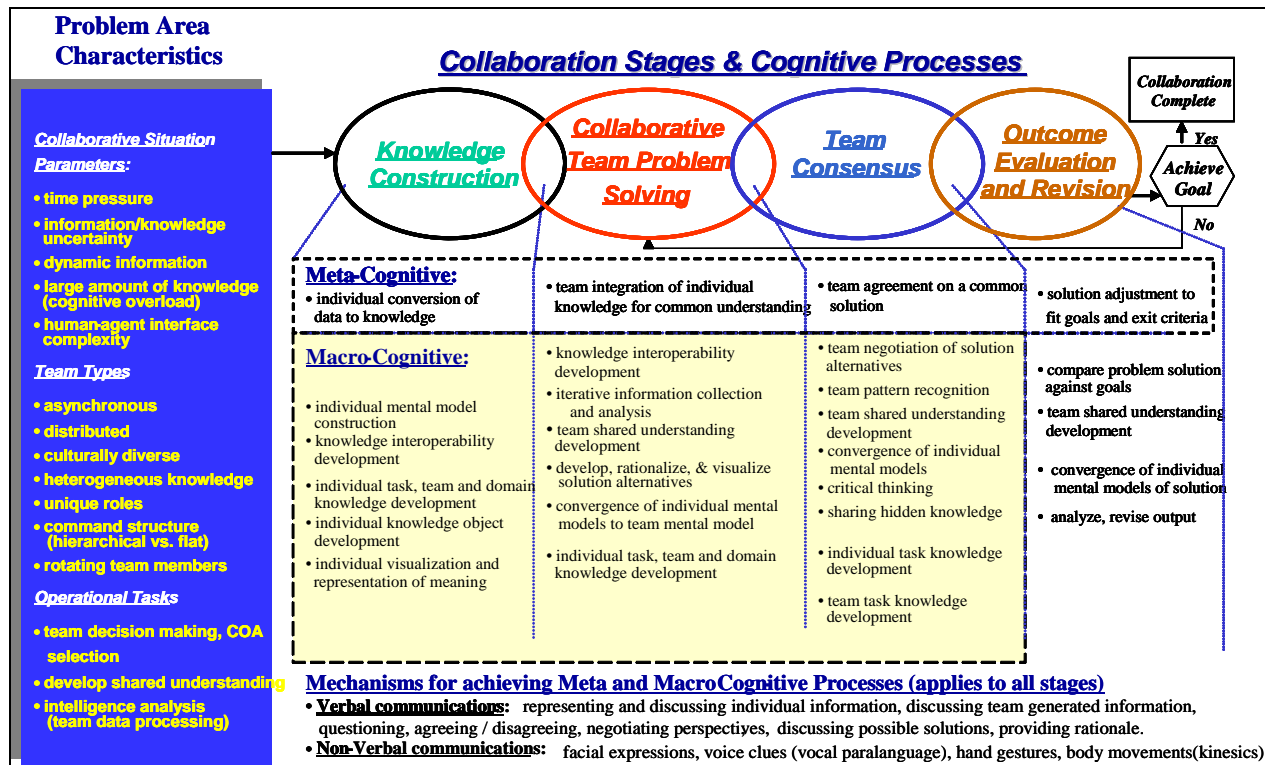


Figure 1. Model of Team Collaboration. (From Warner, Letsky, & Cowan, 2004).

Team Types. Team types described by the model include teams who operate asynchronously, whose members are distributed, and culturally diverse, where members possess heterogeneous knowledge, due to the unique roles played by each team member, and operate in a hierarchical organizational command structure, and in some situations involve rotating team members (Warner, et al., 2004). Members of both the boarding party and air warfare teams each have distinct roles and bring their respective expertise (e.g., radiological detection) to bear, and combine their heterogeneous knowledge.

Four unique but interdependent stages of team collaboration are included in the model. As depicted in Figure 1, the stages include knowledge construction, collaborative team problem solving, team consensus and outcome and evaluation and revision. Cognitive processes within each stage are represented at two levels: meta-cognitive processes, which guide the overall problem-solving process, and macro-cognitive processes, which support team members' activities within the respective collaboration stage. The model's macro-level definition of the cognitive processes permits empirical assessment of these cognitive processes with currently available measurement techniques (e.g., verbal protocol analysis, communication analysis).

Analysis of data captured from teams performing their tasks in a collaborative environment can provide valuable insight into what constitutes effective collaboration performance.

The model focuses on three tasks: (1) team data processing, (2) developing a shared understanding among all team members, and (3) team decisionmaking and course of action selection. The model consists of general inputs (e.g., task description), collaborative stages that the team goes through during the problem solving task, the cognitive processes used by the team and final team outputs, such as the selected course of action.

Knowledge construction begins with team members building individual task knowledge and the construction of team knowledge. Knowledge represents a pattern that connects and generally provides a high level of predictability regarding what is described or what will happen next. The focus of all the macro-level cognitive processes in the knowledge construction stage is to support individual and team knowledge development. This knowledge will be used during collaborative team problem solving sessions to develop solution alternatives to the problem.

During collaborative team problem solving sessions, team members communicate data, information and knowledge to develop solution options to the problem (Bellinger, Castro, & Mills, 2004). The majority of collaboration occurs during this stage (Warner, et al., 2004). The focus of the macro-cognitive processes during this stage is to support development of solution options for the collaborative problem.

During team consensus the team negotiates solution options and reaches final agreement by all team members on a specific option. The macro-cognitive processes support the team in reaching total agreement on the final solution to the problem. During the outcome, evaluation and revision stage the team evaluates the selected solution option against the problem-solving goal and revises the solution option if that option does not meet the goal.

METHOD

Verbatim transcripts were analyzed from two series of experiments where teams collaborated to solve a complex problem. These decisionmaking domains included Maritime Interdiction Operations (MIO) and air warfare decisionmaking scenarios. In both of these problem-solving tasks, assessment is particularly difficult because the available information is often incomplete or ambiguous. Transcripts included communications that occurred between all team members as well as with decisionmakers at the distributed sites. Our approach was to analyze and code team communications data using the cognitive process definitions developed by Warner, et al., (2004). The focus of the collaboration model is on knowledge building among the team members and developing team consensus for selection of a course of action. This research builds on previous work to validate this model (Warner, et al, 2004). The current effort uses a similar methodology applied to two different decisionmaking scenarios.

Experiment I: Maritime Interdiction Operations

An experiment was conducted to test the technical and operational challenges of developing a global Maritime Domain Security testbed. One goal was to test the applicability of using a

wireless network for data sharing during a Maritime Interdiction Operations (MIO) scenario to facilitate expert reach back for radiation source analysis and biometric data analysis. This technology aims to provide networking solutions for maritime interdiction operations where subject matter experts at geographically distributed command centers collaborate with a boarding party in near real time to facilitate situational understanding and course of action selection.

The objective of this experiment was to evaluate the use of networks, advanced sensors, and collaborative technology for rapid MIO. Specifically, the ability for a boarding party to rapidly set-up ship-to-ship communications that permit them to search for radiation and explosive sources while maintaining contact with the mother ship, command and control organizations, and collaborating with remotely located sensor experts.

The boarding team boards the suspect vessel and establishes a collaborative network and then begins their respective inspections and data collection processes. The boarding officer boards the vessel with his laptop so he can collaborate with all other members of the team. This includes those who are located on the ship, but are physically spread out around different areas of the ship (while searching for contraband material and obtaining fingerprints of crew members), as well as the virtual members of the boarding team – the experts who are located at the different reach back centers. Since there are numerous commercial uses for certain radioactive sources, positive identification of the source in a short time is imperative. There is also pressure to conduct the MIO quickly so as to not detain the ship any longer than necessary.

MIO Team Members. Members of the boarding team include the following team members: 1) the Boarding Officer, a Coast Guard officer; 2) a representative from Lawrence Livermore National Labs (LLNL) with portable radiation detection devices and “reach-back” capability to LLNL; 3) a representative from the Defense Threat Reduction Agency (DTRA), who uses biometrics measurements of fingerprints and video imagery to be checked against databases at the remote facility; and 4) a representative from Special Operations Command (SOCOM), who provides guidance on handling hazardous material.

Maritime Interdiction Operations Scenario. Based on intelligence, the US Coast Guard has ordered one of its cutters to stop, board, and search a commercial vessel of foreign origin suspected of transporting uranium enriching equipment. The boarding party brings radiation detection and biometric gear, drawings of dangerous equipment and people, and video recording capability. Data is collected on suspicious material, equipment, and people and sent to specific experts at distributed reach back centers. A network extension capability was utilized from the cutter to the boarding team; the network was able to reach back to LLNL and DTRA to assist in identification of suspect cargo. Support from the National Biometric Fusion Center was used to quickly and accurately discriminate between actual vessel crewmembers and non-crew suspect persons.

The Groove collaborative workspace brought expert services into the boarding party team’s tool set and facilitated voice and text communications between all members of the virtual boarding party and physical boarding party. Remote sites were able to receive and open posted files in less than two minutes to begin their analysis. For example, expert services provided at LLNL quickly determined the need for additional data capture of longer length and different angles of approach.

Requests were transmitted by text message and taken for action, and radiation source spectrum captures were made of suspect containers that were detected to have a radiation signature presence. Analysis of this data led the boarding officer to recommend that the vessel be quarantined for further inspection. The biometric team took digital prints of the crew to be compared to known criminal prints and latent prints from terrorist and crime scenes.

Experiment II: Air Warfare Decisionmaking

Air warfare decisionmaking is conducted in the combat information center of a Navy ship. The team has responsibility for identification of a large number of air tracks under high time pressure. These air tracks can fit multiple hypotheses regarding the level of threat they pose to the battlegroup due to the high level of ambiguity associated with the data. The nature of the data, the complex judgments required, and a sociotechnical environment that is characterized by high workload, and high stakes, all combine to create an extremely challenging problem for the air warfare team.

Incoming information arrives via various sensor systems (radar, electronic support measures system, identification friend or foe, etc.), and various reports, e.g., intelligence reports, other platforms in the area pass messages regarding situation reports on various tracks, and so on. All these reports are passed by the team member who operates that sensor, or who receives the message, to the rest of the team over any of several communications systems. These reports are generally heard by all other team members as they are all on the same communications net, although the reports are typically addressed to a specific team member/s, and sometimes they are addressed to “all.” The two key decisionmakers are the commanding officer and the tactical action officer.

Reports on specific tracks are interleaved with reports on other tracks. Communications between team members are passed as soon as new information is received and updated reports are passed as soon as new information is obtained for any track. So, for example, in a series of speech turns, five separate contacts may be discussed at various levels – initial reports, updated reports, sharing information on the response, or lack of response, by the contact to some action taken by the ship, etc. Five consecutive reports could pertain to five separate tracks or all reports could pertain to one track.

Air Warfare Team Members. Six collocated team members consisted of the commanding officer (CO), tactical action officer (TAO), air warfare coordinator (AAWC), electronic warfare supervisor (EWS), identification supervisor (IDS) and tactical information coordinator (TIC). These combat information center team members also communicated with several non-collocated information sources, e.g., the battle group commander, the Saudi air tower, assets passing intelligence reports, other ships and friendly aircraft in the vicinity of the battlegroup, to gather additional information from them and keep them apprised of the unfolding scenario as they collaborated to identify air tracks.

Air Warfare Decisionmaking Scenario. The global air warfare task involves identification and responding to numerous contacts. When an aircraft (or a surface contact) is detected, CIC personnel work as a team to determine the identity and to try to determine whether or not the

aircraft poses a threat. The high degree of inherent ambiguity associated with contact information can often make threat assessment a very difficult task. This is because many pieces of data fit multiple hypotheses regarding threat assessment. The global response choices (that is, engage, monitor, do nothing) are largely determined by the ship's orders and the current geopolitical situation. Specific actions (such as, change course, issue verbal warnings, illuminate with radar, challenge with other sensors, etc.) depend on the local conditions and the relative positions of the inbound contact of interest and own-ship. Determining which of these actions is likely to be effective depends on maintaining an accurate threat assessment which requires continually updating based on iterative situation assessments.

Critical air contacts are identified based on ambiguous information under time pressure to determine if the track posed a threat to the ship. One of the most challenging aspects of the combat information center teams' job is the high mental workload that is entailed when a constant stream of information must be continuously evaluated, particularly when the information often pertains to several different air contacts (or "tracks"). Relevant data/information items must be associated with the right track number, then analyzed, synthesized and aggregated. This task places an extremely high load on working memory. The air warfare team must assess, compare, and resolve conflicting information, while making difficult judgments and remembering the status of several evolving situations. These tasks are interleaved with other tasks, such as making reports to higher authority and requesting assets.

In general, the overall task of responding to air warfare scenarios consists of situation assessment ("what's going on") and action selection ("what to do about it"). Recent theories of decision-making emphasize the importance of situation assessment for good decisionmaking in naturalistic, event-driven situations (Hutchins, 1995). Moreover, they stress that decisions regarding actions to be taken are a by-product of developing the situation awareness that precedes action selection.

Coding Process

Cognitive process coding definitions developed by Warner, et al. (2004) were used to code all speech turns. The coders attempted to develop criteria for applying the coding schema as a number of coding categories appear to have similar meanings. This codification of the coding process is part of the overall validation of the model, in that one goal is to have high inter-rater reliability between coders. It was important to pay attention to which track a team member was talking about when coding the speech turns. (This could sometimes be challenging because the last time a track was discussed may have several pages previously in the transcript and sometimes the person speaking did not always state the track number that was being discussed. In these situations the rater, by careful reading of the communications, was able to infer which track the speech turn referred to.)

The first time they discussed a track the speech turn was coded as a 2 (*individual mental model* (IMM) construction – where an individual team member, using available information, develops his/her mental picture of the problem situation). After three speech turns that discussed the same track (typically involving at least four, of the six or more team members) it was coded as a 4 (*team knowledge development* (TKM) – where all team members participate in clarifying information to build team knowledge. Once five-six team members had discussed a track, and at

least 4 of the 6 team members had been involved in discussing this particular track, it was coded as a 10 – team shared understanding development – which includes discussion among all team members on a particular topic or data item.

Some exceptions to the above mentioned coding criteria include: When a team member addresses “All stations, [track # 7010 is a comm-air.]” this means he is telling all team members this evaluation of the track. Because it was addressed to all team members and it reported a higher level/ more final assessment of the track, i.e., it is a commercial airliner, this was coded as a 10. As more team members get involved in discussing a contact (i.e., more reports and/or updates have been shared among team members, the cognitive process coding category reflects a higher level of team understanding of the situation regarding that particular track.

RESULTS

Table 1 presents the cognitive process definitions developed for the model of team collaboration. We added new examples for each coding category, based on our analysis of the air warfare scenarios, to provide illustrative examples of the types of communications that fall under each of the coding categories. (The original set of cognitive process definitions included examples from a non-combatant evacuation scenario.) These examples of the coding categories are contained in Table 1.

New Coding Categories

During the analysis phase new coding categories emerged when coding the air warfare scenarios. These new categories include 21–23, miscellaneous, issue an order regarding a course of action, and request a person take some action. Examples of these categories are included in Table 1 which includes the original coding categories. *Miscellaneous* category includes getting the attention of a team member (e.g., “TAO this is EW”) prior to speaking (so as not to waste time speaking if the team member is busy and not ready to listen to the message), acknowledging a request to speak, acknowledging a message, e.g., “Copy all,” and issuing a verbal warning to the potential threat track over the radio system. Because standard operational procedure for communicating requires that significant communications be acknowledged, this wound up being the largest category of communications.

Issuing an order regarding a course of action appears to be a significant coding category. This refers to situations where a person with higher rank (e.g., commanding officer speaking to the tactical action officer (TAO), or the TAO speaking to one of the enlisted system operators, tells them to take some specific action against a potential threat track. These actions include issuing verbal warnings, illuminating or locking-on with radar, developing a firing solution, covering with missiles, etc. This category also includes responding/ reporting they have taken the action, or acknowledging the order.

Request a team member take some action refers to telling a team member to do something but it is not a direct action against a threat track. For example, “Can you try and change 7006 and 7005 to assumed hostile. I keep trying and can’t get it to do it.”

Other potential new categories include *Prodding a team member* to jog their awareness, e.g., to make sure they are following the discussion, or they push or suggest to one or more team members to go out and generate knowledge, e.g., “You should go back and see if there is ...”. This person directing or suggesting might act in a role as teacher gently pushing the collaborative effort in a certain way. Another potential new category is for “*Contrarians*” when a person says “Let’s re-evaluate/ reconsider, or when the person disagrees with the current thinking of the team. This would be an “outlier” who makes the team consider another viewpoint, or “pulls back the reins.” As additional scenarios are analyzed and coded new categories may emerge.

Table 1. Cognitive Process Definitions
(From Warner, Letsky, and Cowan, 2004)

Cognitive Process Definitions	
1.	<p>Metacognition dti: individual conversion of data to information = individual team member converting data to information.</p> <ul style="list-style-type: none"> • “We have Don-2 bearing 086 and LN-66 bearing 097.”(converted detected radar parameters –<i>data</i> to <i>information</i> – names of radars on specific bearings) • “I am showing 8044 at 400 knots and about 27 thousand feet, possible comm-air type profile.” • “I have a second contact at 1000 feet.”
2.	<p>Macro cognition imm: individual mental model construction = individual team member, using available information, develops his/her mental picture of problem situation.</p> <ul style="list-style-type: none"> • “8030 definitely originated from Iranian airspace? The possible helo?” • “That’s affirmative, sir.” • “APQ-120 bears 072 off possible Foxtrot 4 Delta or Echo.” • “We have 8053, that air unknown coming in up there.” • “2017 is squawking a comm-air mode 3. In company with 2025, but that track is much lower than the comm-air. One at 37000, one at 8000 just came in low.”
3.	<p>Macro cognition itk: individual task knowledge development = <u>individual</u> team member asking for clarification to data or information; response to clarification.</p> <ul style="list-style-type: none"> • “Do we have the track number for his CAP? I would prefer to have the track number for his CAP.” • “Are you covering with birds?” • “That’s affirmative, sir.” • “Did you illuminate him?” (clarifying action has been taken) • “Did you establish communications with him?” • “Since he is turning to the east do you still want us to continue with level one?” (clarification of actions to be taken) • “That’s a negative.” (response) • “The Desert Eagle don’t have that information for you right now. I asked them to get that for us. Whether the F-1s were clean or dirty.”
4.	<p>Macro cognition tk: team knowledge development = All <u>team members</u> participate in clarifying (i.e. answering a question) information to build team knowledge.</p> <ul style="list-style-type: none"> • “Rainbow is sending Desert Eagle 101 and Desert Eagle 102 over to investigate track 8037 (TN 7034).”

	<ul style="list-style-type: none"> • “He looks like he is on a [air] corridor, Kuwait City to Bushehr.” • “Received ESM of Cyrano 4 bears 121 off the F-1.” (I) --- information • “No response track 8070.” (I) --- information • “I don’t have mode 3 or any other type of IFF available to me right now.” • “They’re going too fast for that.” • “Looks like he’s comm-air, he’s high and looks like a comm-air profile.”
5.	<p>Macro cognition ko: knowledge object development = pictures, icons or standard text, developed by an individual team member or the whole team, that represents a standard meaning to the team.</p> <p>--- [No coded examples for air warfare]</p>
6.	<p>Macro cognition vrm: individual visualization and representation of meaning</p> <p>Visualization = individual team members use methods (e.g., graphs, pictures) to transfer meaning to other team members.</p> <p>Representation = individual team members use methods to sort data and information into meaningful chunks.</p> <p>--- [No coded examples for air warfare]</p>
7.	<p>Metacognition cu: team integration of individual knowledge for common understanding = <u>all</u> team members combine individual pieces of <u>knowledge</u> to achieve a common understanding.</p> <ul style="list-style-type: none"> • “Track 7005 has turned west and is now inbound, sir.” • “He’s holding in altitude, he’s not far from the air way, he flew out of good guys country and we have a comm-air radar. Let’s make him assumed friend.”
8.	<p>Macro cognition kio: knowledge interoperability development = team members exchanging <u>knowledge</u> among each other.</p> <ul style="list-style-type: none"> • “Desert Eagles report “tally ho” on section of two Iranian F-1s, out.” --- (derived knowledge from aircraft providing a visual identification) • “We have Primus 40, bears 135, Gulfstream 2, possible Super Puma.” • “It looks like the AWACs is feet dry. The CAP, composition 2, appear to be headed feet dry now.” • “Doctrine won’t work for 2017, make unknown assumed enemy.”
9.	<p>Macro cognition ica: iterative information collection and analysis = <i>collecting</i> and <i>analyzing</i> information to come up with a solution but <u>no specific solution mentioned</u>.</p> <ul style="list-style-type: none"> • “No response initial warning, track 8037.” • “We need a report from CAP as to whether those, upon intercept of those suspected Pumas, whether they are armed or not.” • “Track 2017 deviated from known flight path still maintaining altitude and still squawking the same mode 3.”
10.	<p>Macro cognition tsu: team shared understanding development = discussion among <u>all</u> team members on a particular topic or data item (i.e. discussion does not involve answering questions)</p> <ul style="list-style-type: none"> • “Track 8061 bearing 027 Princeton at 25 miles, 5000 feet, heading south, covering with birds.” • “It looks like he is turning to the west.” • “You need to watch him closely here.” • “Track 8061 appeared to originate from Iran. When we picked him up he was already off the coast but he was coming south from close to the Iranian coast. I can’t confirm that he came from Iran but he was coming from that direction.” • “I am showing a CPA of 43 miles to the south at their current heading.”

	<ul style="list-style-type: none"> • “Cyrano 4, that emitter has ceased. Last bearing for Cyrano 4 was 122.” • “OK, what do we think about the Saudi CAP? Shot down, too low to communicate?” • “It looks like we still have a good track on them, 27 at 13000. Probably just poor comms with the AWACS.” • “Continue to track sections of Iranian F-1s and F-4s. Approached the force with an attack profile. Interrogated level 1 with no response. They turned away from the force at a range of about 30 miles. Continuing to track.”
11.	<p>Macro cognition sa: develop, rationalize and visualize solution alternatives = using data to justify a solution</p> <ul style="list-style-type: none"> • “I would like fire control lock up on 7010 and I’d like to make sure he is designated as a gun target. I’d like to have two rounds of illumination prepped on mount 52.” • “My intentions are to issue a warning shot with a flare if the helo proceeds to within ten nautical miles, over.” • “Indicate to 7010 that if he continues to close he can expect defensive actions.” • “Track number 7010 continuing inbound, request permission to engage at three nautical miles, no response to all measures, so far.”
12.	<p>Macro cognition cmm: convergence of individual mental models to team mental model = convincing other team members to accept specific data, information or knowledge</p> <ul style="list-style-type: none"> • “OK, we need to make them assumed enemy and cover them, AAWC.”
13.	<p>Metacognition cs: team agreement on a common solution = all team members agree on the <i>final plan</i>.</p> <ul style="list-style-type: none"> • “Listen up. 8044 is a probable comm-air, 8100 is an assumed hostile.” • “8044 looks like a comm-air profile.” • “ID 2010 unknown assumed friend.” • “Request batteries release on track 7010, it is continuing inbound, he is at three nautical miles, request permission to engage, over.”
14.	<p>Macro cognition tn: team negotiation of solution alternatives = team negotiation of solution alternatives ending in a final solution <i>option</i>. (solution options are defined for each of the five components of the final plan --- i.e. personnel, transportation, weapons, critical times and detail plan) --- [No coded examples for air warfare]</p>
15.	<p>Macro cognition tpr: team pattern recognition = the team as a whole identifies a pattern of data, information or knowledge. --- [No coded examples for air warfare]</p>
16.	<p>Macro cognition ct: critical thinking = Team working together toward a common goal, whereby goal accomplishment requires an active exchange of ideas, self-regulatory judgment, and systematic consideration of evidence, counterevidence, and context, in an environment where judgments are made under uncertainty, and there is limited knowledge and time (Hess & Freeman, 2004).</p> <ol style="list-style-type: none"> 1. <u>critical thinking is measured as a composite of:</u> (Warner & Wroblewski, 2004; Hess & Freeman, 2004) <ul style="list-style-type: none"> • MCitk: individual task knowledge development = individual team member clarifying data; asking for clarification. • MetCcu: team integration of individual knowledge for common understanding = one or more team members combine individual pieces of knowledge to achieve a common understanding.

	<ul style="list-style-type: none"> • MCkio: knowledge interoperability = team members exchanging <i>knowledge</i> among each other. • MCsa: develop, rationalize and visualize solution alternatives = using data to justify a solution <p>Note: one critical thinking frequency count = oneMCitk +oneMetCcu + MCkio + MCsa</p>
17.	<p>Macro cognition shk: sharing hidden knowledge = individual team members sharing their knowledge through prompting by other team member(s).</p> <ul style="list-style-type: none"> • “We still have no level two warnings out to those guys.” • “Yes sir, we ID’d him as a com[mercial] earlier, we will go ahead and talk to him.” • “I’ve got track 7011 ID’d as com-air. He started out at 35,000 feet, now he is descending.”
18.	<p>Metacognition sag: solution adjustment against goal and exit criteria = team as a whole compares complete solution option against goal and exit criteria.</p> <ul style="list-style-type: none"> • “Ceased illumination 8005, maintaining lock on 8005. Turning outbound.”
19.	<p>Macro cognition csg: compare solution options against goal(s) = team members discuss solution options (i.e. any of the five solution components) against the scenario goal (i.e. rescue 3 red cross workers within 24 hrs).</p> <ul style="list-style-type: none"> • “Ah Rainbow’s holding track number 7011, low and slow and inbound. Do you desire me to cover with birds also?”
20.	<p>Macro cognition aro: analyze, revise solution options = team members analyze final solution options (i.e. any of the five solution components) and revise if necessary.</p> <p>--- [No coded examples for air warfare]</p>
21.	<p>Miscellaneous: misc = acknowledging a message, asking for repeat of message, verbal warning</p> <ul style="list-style-type: none"> • “Copy all, out.” • “What was your last?” • Verbal warning issued to inboard aircraft
22.	<p>Issue order regarding a course of action: coa = a superior in the chain of command tells a team member to take a specific action against a possible threat track.</p> <ul style="list-style-type: none"> • “Cover 8032 (TN 7013) with standard missile also generate a SWG 1A solution on him.” • “Cease illumination.” • “Let’s start level ones, 8070.”
23.	<p>Request take action: rta = team member requests another team member take some action.</p> <ul style="list-style-type: none"> • “Let’s investigate with CAP.” • “Confirm that tracks originating from Iranian air space are designated unknown assumed hostile.” • “Have SWC develop a Harpoon solution on him.” • “Go ahead and tag 8037 as F-1s.” • “Make 8037 and company assumed hostile.” • “Shift your focus Air to 8070, inbound helo.” • “Increase speed as well.”

For the MIO scenario, 52% of the speech turns contained content related to solving the problem; 48% involved administrative types of communications. Evidence for twelve of the twenty-two cognitive processes included in the model were found. For the air warfare scenario, 99% of the speech turns contained content related to solving the problem; 1% involved administrative types of communications. Evidence for fifteen of the twenty-three cognitive processes included in the model were found. Multiple occurrences for most of these cognitive processes were found in both scenarios.

Table 2 presents the cognitive process coding tallies for the four air warfare scenarios. The large number of speech turns coded as itk reflects the high degree of uncertainty inherent in air warfare decisionmaking tasks. An interesting example of sharing hidden knowledge (17) occurred when the CO issued an order to issue a verbal warning and “lock up” the inbound aircraft. The next speech turn involved the TAO replying “Yes, sir, we identified him as a com[mercial aircraft] earlier, we will go ahead and talk to him.” In this situation, the TAO was gently reminding the CO of a critical piece of information that he had forgotten. The large number of speech turns coded as categories 1-4 reflects the huge emphasis on individual knowledge construction for the air warfare task. Similarly, that examples of all six categories in the collaborative team problem solving phase – where teams integrate individual knowledge for common understanding – had many speech turns coded as these categories also indicates the large role these cognitive processes play for air warfare teams. In contrast, the small percentage of speech turns that were coded as cognitive processes associated with team consensus and outcome evaluation and revision indicated that the course of action selection phase of air warfare is not conducted in a collaborative manner.

Table 2. Cognitive Process Coding Tallies for Air Warfare Scenarios

		Scen D- Run A	Scen D- Run B	CG 59	DDG 54
1.	Data to information (dti)	1	4	--	37
2.	Individual mental model (imm)	8	11	18	25
3.	Individual task knowledge development (itk)	25	30	31	29
4.	Team knowledge development (tk)	11	5	18	1
5.	Knowledge object development (ko)	--	--	--	--
6.	Visualization and representation (vrm)	--	--	--	--
7.	Common understanding (cu)	--	6	--	
8.	Knowledge interoperability (kio)	--	5	--	1
9.	Iterative collection and analysis (ica)	1	11	--	--
10.	Team shared understanding (tsu)	1	17	28	34
11.	Solution alternatives (sa)	--	3	--	--
12.	Convergence of mental models (cmm)	1	--	--	--
13.	Agreement on Common solution (cs)	--	2	--	--
14.	Team negotiation (tn)	--	--	--	--
15.	Team pattern recognition (tpr)	--	--	--	--
16.	Critical thinking (ct)	--	--	--	--
17.	Sharing hidden knowledge (shk)	--	2	--	--
18.	Solution adjustment against goal (sag)	--	--	--	--
19.	Compare solution options against goals (csg)	--	1	--	--

20.	Analyze, revise solutions (aro)	--	--	--	--
21.	Miscellaneous (misc)	38	27	57	61
22.	Issue order regarding course of action (coa)	7	5	17	37
23.	Request take action (rta)	3	2	18	8

Table 3 presents an excerpt of the communications coding from the MIO scenario where the team is developing solution alternatives by using data to justify a solution. First (1), individual TMs are clarifying data regarding the degree of danger inherent in the material discovered (2) and exchanging knowledge among each other, i.e., the material needs to be confiscated (3), based on information provided by one of the remote centers (the material needs to be handled carefully). An individual exchanges knowledge with other TMs (4) to develop knowledge interoperability regarding whether the Coast Guard ship has a suitable storage area for the confiscated material (5). Finally, TMs combine individual pieces of knowledge to achieve a common understanding (6) regarding the next action to be taken.

**Table 3. Excerpt from MIO Scenario Communications Coding:
Developing Solution Alternatives**

MIO Team Communications			Cognitive Process Coding	
	Speaker		Code	
1	DTRA	Cesium 137 can be used to make an RDD. If there are no explosives, then it is not configured as a weapon yet. Recommend material be confiscated.	MCsa	Develop, rationalize and visualize <i>solution alternatives</i> ; using data to justify a solution
2	BO	Roger will confiscate.	MCitk	<i>Individual task knowledge</i> develop-ment; individual TM clarifying data.
3	BO	Make sure you handle carefully. Cs-137 is an external gamma hazard.	MCKio	<i>Knowledge interoperability</i> : TMs exchanging <i>knowledge</i> among each other.
4	BO	Roger. Will take precautions.	MCKio	<i>Knowledge interoperability</i> : TMs exchanging <i>knowledge</i> among each other.
5	SOCOM	Does CG ship have proper storage area for material confiscated?	MCitk	<i>Individual task knowledge</i> development: individual TM clarifying data, asking for clarification.
6	SOCOM	Search team will report size of material and its current containment condition; then make recommendations.	MetCcu	Team integration of individual TM knowledge for <i>common understanding</i> ; one or more TMs combine individual pieces of knowledge to achieve common understanding.

**Table 4. MIO Scenario Communications Coding:
Knowledge Interoperability Development and Agreement on a Final Plan**

MIO Team Communications			Cognitive Process Coding	
	Speaker		Code	
1	BO	Negative for explosives Station 2.	MCKio	<i>Knowledge interoperability</i> : TMs exchanging <i>knowledge</i> among each other.
2	LLNL	Finally received RAD data from	MCKio	<i>Knowledge interoperability</i> : TMs exchanging

		station 2.		<i>knowledge among each other.</i>
3	SOCOM	Will need to resolve RAD containment hazard if it exists.	MetCcu	Team integration of individual TM knowledge for <i>common understanding</i> ; one or more TMs combine individual pieces of knowledge to achieve common understanding.
4	DTRA	If you have plutonium, you need to confiscate. It's an alpha hazard, but still must be handled carefully.	MCKio	<i>Iterative information collection and analysis; collecting and analyzing information to come up with a solution but <u>no specific solution exists.</u></i>
5	BO	Roger.	Misc	Acknowledge report.
6	DTRA	By the way, if plutonium is in solid metal form, your team can handle safely with rubber gloves and a dental face mask, depending on how much is there.	Macica	Team shared understanding development – discussion among <u>all</u> team members on a particular topic or data item..
7	BO	Talking to search team to see if this is within their capabilities or if we will need outside assets.	MCKio	<i>Iterative information collection and analysis; collecting and analyzing information to come up with a solution but <u>no specific solution exists.</u></i>
8	LLNL	Hazard is probably minimal, can isolate and confiscate.	Metcs	Team agreement on a common solution – all tem members agree on the <u>final plan.</u>

DISCUSSION

Differences between the two scenarios in terms of how the team's behavior maps to the model of team collaboration were noted. One difference was that course of action selection during the air warfare tasks tends to be done less collaboratively than it is in other decisionmaking domains, e.g., a maritime interdiction operation scenario, due to the inherent time pressure to make decisions and take actions. Decisions tend to be made unilaterally by the tactical action officer or the commanding officer, (sometimes these two collaborate) but do not typically involve discussion with the rest of the team. Decisions regarding course of action selection entailed very little collaboration for the air warfare tasks due to the speed of the potential threat aircraft. When actions need to be taken very quickly in an attempt to determine the intent of an inbound track, and a series of gradually escalating actions are required, time is not available to discuss alternative courses of action.

In general, the overall task of responding to air warfare scenarios consists of situation assessment ("what's going on") and action selection ("what to do about it"). Klein (1989) found that when decisionmakers use a recognition-primed decisionmaking strategy to perform decisionmaking tasks, usually the situation itself either determines or constrains the response options and that experienced decisionmakers make up to 90% of all decisions without considering alternatives. If the situation appears similar to one that the decision maker has previously experienced, the pattern will be recognized and the course of action is usually immediately obvious. The recognition primed model of decisionmaking fuses two processes—situation assessment and mental simulation (Klein, 1993). In the simplest case the situation is recognized as familiar or prototypical, using feature matching, and the obvious response is implemented. In a more complex case the decisionmaker performs a conscious evaluation of the response, using mental simulation to uncover problems prior to implementing the response. In the most complex case

the evaluation reveal flaws requiring modification, or the option is judged inadequate and rejected in favor of the next most typical reaction.

CONCLUSIONS

Analysis of data captured from teams performing their tasks in a collaborative environment can provide valuable insight into what constitutes effective collaborative performance. This understanding can then be used to develop technology to support this cognitive activity, develop tools to reduce cognitive workload, and techniques and processes to improve information exchange among collaborating members. Future plans include additional analysis for more complex scenarios and analysis of the contribution made by providing collaborative tools to support teams when performing these collaborative tasks.

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